A TYPE OF IGNEOUS DIFFERENTIATION[1]

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CONTENTS

INTRODUCTION

This paper begins with a summary description of the rock types of the Duluth gabbro formation, and suggests the processes by which they formed. Since there are similar rock series in other districts, where the relations of large intrusions are not so clear, or where the study has been less detailed, it is suggested that the same processes are indicated in those districts. This type of differentiation, therefore, is not at all unique.

[1] Published by permission of the Directors of the Minnesota Geological and Natural History Survey and the United States Geological Survey. Part of a dissertation presented at Yale University.

THE ROCKS OF DULUTH

The Duluth gabbro and its differentiates are intrusive into Middle Keweenawan flows, probably at a considerable depth. At Duluth it is evident that a feldspathic gabbro was intruded and cooled before the main mass of more basic gabbro was intruded. The mass is so large that it must have required thousands of years to cool, plenty of time for its differentiation into the many types now found. Some differentiates assume an intrusive relation to those earlier to crystallize, the most conspicuous case being the intrusion of "red rock," or granophyr, into gabbro. When studied in detail the mass shows by the intimacy of the geologic connection that, with all its variety, it is essentially a single geologic unit. Not only is the red rock related to the gabbro by association and intermediate phases, but over most of the area the two portions of the gabbro cannot be distinguished. Even at Duluth the two masses are not everywhere distinguishable. The averages differ only about 10 per cent in the amount of feldspar. It is believed that no great error will be introduced if the whole mass of data on the Duluth gabbro is considered as a unit. The main gabbro at Duluth and in many other outcrops is conspicuously banded.[1] The form has been named a lopolith[2] (Fig. 1).

The descriptive petrography of the formation need not be rewritten here in detail.[3] However, this study adds a few points from the type locality, where the exposures are exceptionally clear. The new data also make it possible to present a consistent, though not at all final, summary of the petrography of the whole mass.

THE GABBRO

The diagrams of the modes from measurements (Fig. 2) and the norms from analyses (Figs. 3 and 4) show the variation in the two gabbro masses at Duluth, without regard to position in the mass. It is evident that no simple linear series could be arranged on the

[1] Frank F. Grout, "Internal Structures of Igneous Rocks," *Jour. Geol.*, XXVI (1918), 439.

[2] Frank F. Grout, "The Lopolith," *Am. Jour. Science*, XLVI (1918), 516.

[3] The references and a correlation of the varying nomenclature are given by A. N. Winchell in *U.S. Geol. Sur. Mon. 52*, pp. 395–407.

basis of mineral composition. The main gabbro types shown in the diagram, even those of extreme composition, occur as alternating bands.

The average gabbro is gray when fresh and weathers nearly white. The texture is medium to coarse, granitoid to ophitic (see Fig. 5). The order of crystallization is in most cases plagioclase, olivine, magnetite, and augite. Olivine is not conspicuous in the

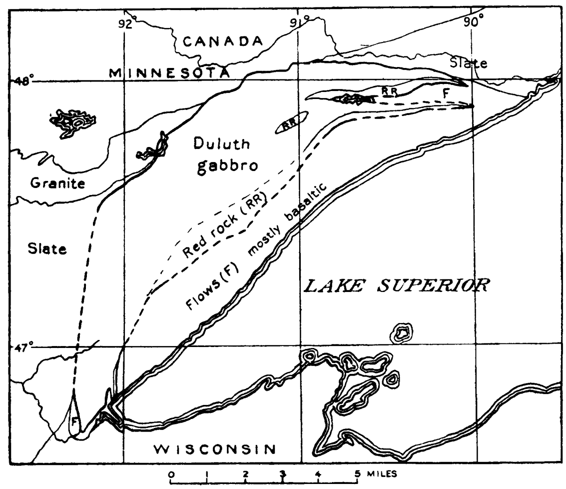

FIG. 1.—Sketch map of the Duluth gabbro area

average gabbro except on the weathered surface, where, being highly ferruginous, it turns to a bright brown, contrasting with the darker augite and iron ores. There is very little alteration. The character of the main minerals is surprisingly constant from end to end of the series of outcrops. All the olivine has about 30 per cent FeO whether in peridotite or anorthosite. There are few outcrops in which the feldspar differs much from Ab_1An_2. The pyroxene, with few exceptions, is augite low in lime.

The rocks of the gabbro series may be classified as normal gabbro, olivine gabbro (and the corresponding diabase, Fig. 5), troctolite, peridotite, magnetite gabbro, and anorthosite. Several specimens might show some further variation, but their occurrence is local and there is no evident importance in the distinction. The

pegmatitic phases have been discussed elsewhere.[1] The analyses tabulated below show the composition of the abundant types.

Peridotite phase.—Bands of peridotite occur in the banded gabbro a few yards above the base. The large bands are over

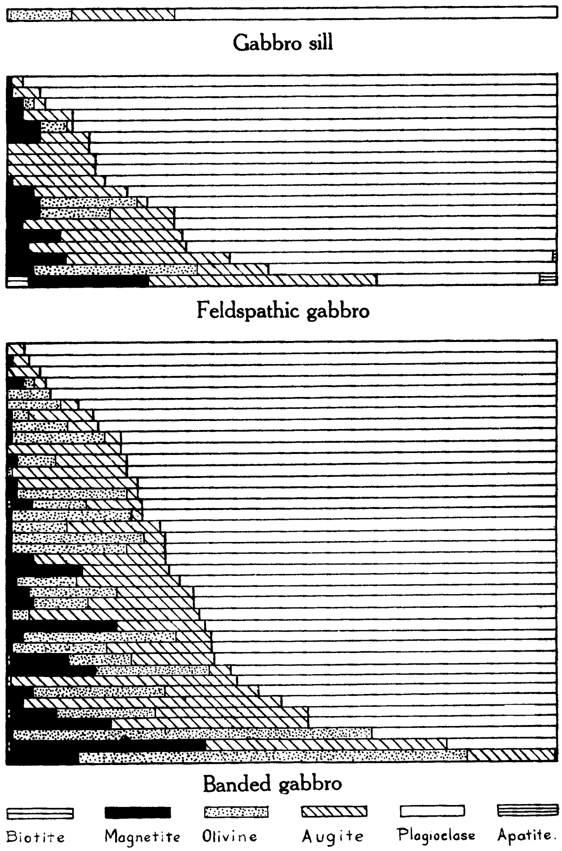

FIG. 2.—Diagram of measured modes of Duluth gabbro

15 feet thick and somewhat variable. They are nearly black, weathering rapidly to a crumbling brown soil. Analysis number 2 in Table I shows the chemical composition, and the diagram (Fig. 2) indicates the mineral composition.

[1] Frank F. Grout, "The Pegmatites of the Duluth Gabbro," *Econ. Geol.*, XIII (1918), 185.

Troctolite phase.—Troctolite, rich in olivine, like that described by Winchell,[1] occurs from the center to the base of the mass, in scattered bands. See analysis number 6 in the table. The proportion of olivine to plagioclase in the several troctolites varies widely, so that the rocks approach peridotite on one side and anorthosite on the other.

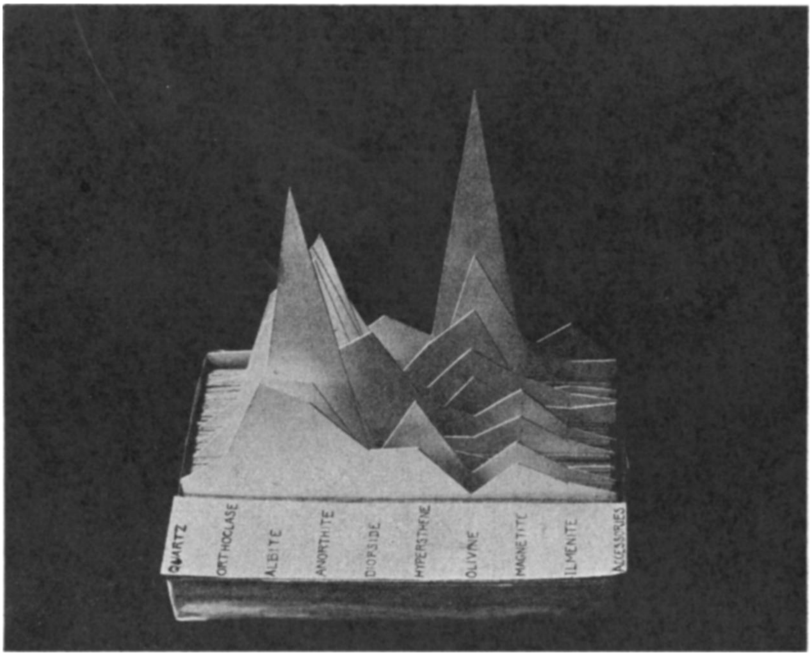

Fig. 3.—Diagram of the norms of analyses of gabbro at Duluth. Many phases have not yet been analyzed.

Anorthosite phase.—At Duluth the early feldspathic gabbro probably contains over 80 per cent plagioclase. Large parts of it by a slight process of differentiation become anorthosite. Analysis 3 of the table is a fair sample, but large masses are even purer feldspar. The later more basic gabbro has less anorthosite, but thin bands of it are not at all rare. An outcrop in Sec. 26, T. 50 N., R. 15 W., resembles the famous anorthosite inclusions in diabase

[1] A. N. Winchell, "Gabbroid Rocks of Minnesota," *Am. Geol.*, XXVI, 281–85.

sills along the shore of Lake Superior. The rock is a conspicuously spotted one (Fig. 6). The darker spots are large poikilitic olivine grains inclosing plagioclase and the white ground mass is feldspar with only a small trace of magnetite. Unfortunately the boundaries of this spotted rock are concealed.

Magnetite phase.—It is possible to find specimens and thin bands of gabbro near Duluth bearing as much as 36 per cent of titaniferous

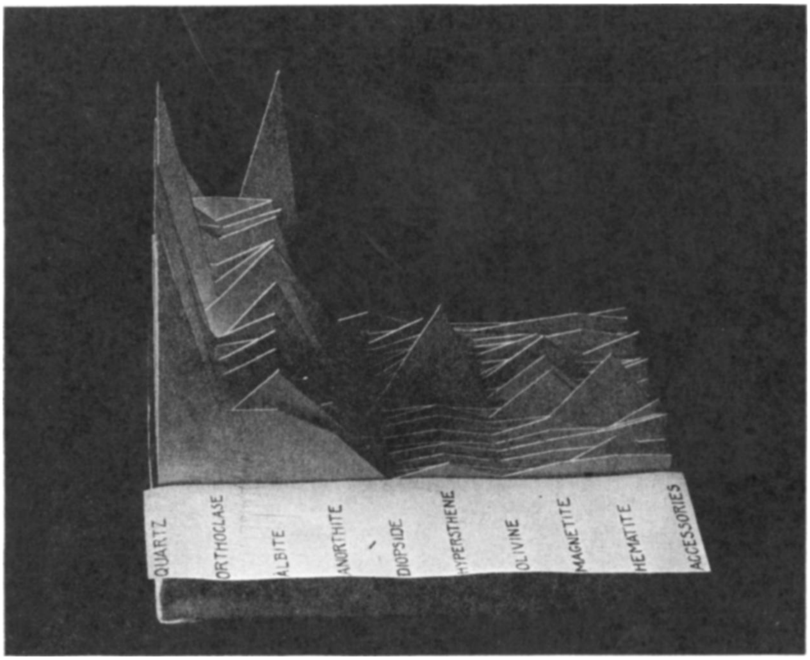

FIG. 4.—Diagram of the norms of analyses of red rock of the Duluth gabbro formation.

magnetite. The bands are near the center of the gabbro, which is nearly three miles thick. There is no olivine in the magnetite rock, but augite is more abundant than in the average gabbro. The band shows fluxion structure, but the minerals seem to have crystallized about simultaneously, magnetite late in some (Fig. 5). Similar bands in Cook County, one hundred miles northeast, much larger and richer in magnetite, make up the titaniferous iron ores for which the gabbro is famous.

THE RED ROCK

Introduction.—The "red rock" has purposely been left out of the discussion of variations from the gabbro, not because it differs from the gabbro more radically than anorthosite differs from peridotite, but because its geologic relations are very different. It has not been seen as bands in banded gabbro. The change from gabbro to red rock is somewhat abrupt and without alternation. The gray gabbro rapidly gives place to a bright red rock very different from the gabbro in mineral, chemical, and physical characters.

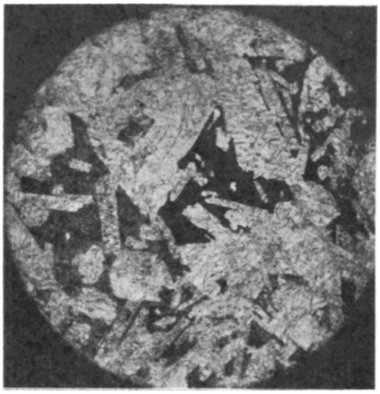

FIG. 5.—Thin section of Duluth gabbro showing diabasic texture. White to light gray, basic labradorite; dark gray, augite; black, magnetite which is late to crystallize. Plain light, ×20.

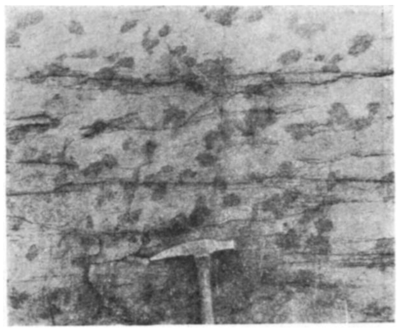

FIG. 6.—Spotted anorthosite. The dark areas are olivine crystals, which poikilitically inclose thousands of smaller plagioclase grains.

The "red rock" has become widely known under this name because of its brilliant color and the difficulty of giving it a more accurate classification. Some confusion may arise also from the fact that red felsitic flows appear in the Keweenawan series. The rock here discussed is intrusive and granitoid.

The chief outcrops near Duluth are irregular patches at the top of the main gabbro and apophyses into its roof; it occurs also near the top of the earlier feldspathic gabbro, in a large sill close above the gabbro, and in some small dikes near the bottom of the gabbro.

Description.—The texture varies from sugary near contacts to very coarse in certain patches. The rock is peculiarly friable, so that

hand specimens can hardly be trimmed from it. A striking local variation contains long needles of dark minerals in a red matrix. In thin sections it is micropegmatitic, varying to granitoid in some large masses. Miarolitic cavities are numerous in some places. Variability is as characteristic of the minerals as of the textures. The chief red mineral is a feldspar stained with considerable hematite and badly kaolinized. Probably most red rock contains two feldspars; zoning is especially common in the phases grading into the gabbro. Quartz, though abundant, is rarely visible except with the microscope as an intergrowth. Hornblende is the chief ferromagnesian mineral, but it is fibrous and mixed with secondary minerals as if itself secondary. Biotite is rare and in most cases secondary.

A sample of the red rock was selected from the type locality for analysis (number 25 of the table), and while it cannot fully represent so variable a rock, it shows some features in common with earlier analysis also quoted in the table. Nearly all the norms include corundum; many also include hematite. For a rock consisting largely of graphic intergrowth of quartz and feldspar—supposed eutectic proportions—the quartz is high and alkalies are low. The lime and potash, both being low, make the rock resemble bostonite in composition, but it is more quartzose than that type. Winchell[1] has tabulated the terms used in the common qualitative system for the red rocks. Possibly granophyr is appropriate for most of the rock.

Gradation and relations.—In the sill in the eastern part of the city there is a remarkable example of perfect gradation from diabase to red rock. The diabase is of ordinary type, with a finer contact phase at the base. It is exposed almost continuously for a width of a mile, equivalent to a thickness of several hundred feet. The diabase grades up into a red-rock zone of smaller thickness and less regularity, though a belt may be followed several blocks. It is noteworthy that while the sill must be nearly 1,500 feet thick, the conspicuous gradation zone is less than 50 feet, from black diabase to intensely red granophyr.

[1] A. N. Winchell, "Review of Nomenclature of Keweenawan Igneous Rocks," *Jour. Geol.*, XVI (1908), 765–74.

A somewhat different gradation is observed in Lincoln Park and near the top of the inclined railroad to Duluth Heights. In these places it is possible to select samples showing all stages between gabbro and red rock, but the relations are not those of a regular zone. The upper part of the banded gabbro shows many local patches with interstitial red granophyr, grading into dikelike stringers and patches of red rock of complex form and relations (Fig. 7). Many of these stringers with sharply defined walls can be traced along their length into less sharply defined markings and finally grade imperceptibly into the black gabbro which formed the walls a few feet away. Both the gabbro and the red rock intrude the roof, sometimes in the same crack, sometimes more distinctly. Although a considerable part of the red rock is so much later in time of solidification that it could intrude the gabbro, the texture of the red rock is coarse up to its contacts and grades into that of the gabbro without a break, indicating that they were about equally hot. The irregularity in the form of the stringers may also be a sign that the gabbro was not wholly solid (see Fig. 7). Such a relation may be properly described as that of an aplite.

Similar relations of gabbro to red rock, both gradational and aplitic, are easily traced for many miles along the belt at the northeast end of the gabbro in Cook County, where the combined thickness is so reduced as to make the mass more like a sill, and the red rock constitutes a larger proportion of the intrusion than at Duluth. The same relation may be expected in the central, thicker part of the gabbro mass,[1] but this has not been mapped in detail as yet (see Fig. 1).

A third gradation from red rock to gabbro is that in the pegmatites near the base.[2]

Origin of the red rock.—All three of these occurrences of red rock and gradations would seem from field studies to be clearly attributable to a differentiation. However, this sweeping assignment of the granophyr to differentiation ignores a whole group of occurrences

[1] This is not wholly in agreement with the brief statements in *U.S. Geol. Sur. Mon. 52*, pp. 374–75.

[2] Frank F. Grout, "The Pegmatites of the Duluth Gabbro," *Econ. Geol.*, XIII, (1918), 185.

which are characteristic of the contacts of diabase with acid rocks. The association is too striking to be thus ignored. At Duluth the case is illustrated by a very narrow granophyr zone at the base of an extrusive diabase north of Short Line Park, where it overflowed a quartzose sand. Where such flows rest on the other flows no

FIG. 7.—Aplitic stringers of red rock in the Duluth gabbro, near the top

such granophyr has been detected. Again, at Pigeon Point a gabbro seemingly related to the Duluth gabbro has inclusions of quartzite which are characterized by a complete inclosing shell of red rock.[1] The composition of the red rock in these cases is not such as can be derived from the sediment, nor from the average

[1] W. S. Bayley, "The Rocks of Pigeon Point," *U.S. Geol. Surv. Bull. 109*, p. 101; R. A. Daly, "The Geology of Pigeon Point," *Am. Jour. Sci.*, XLIII, 423.

magma, nor any possible mixture. Mr. T. M. Broderick, of Minnesota, has recently checked up the previous work on the chemical nature of the rocks by determining the alkali content of all the rocks at the contact of gabbro with an inclusion of quartzite. If red rock in this situation is derived from quartzite it is derived from the immediately adjacent inclusion. The gabbro has 3.49 per cent alkali and the quartzite 3.60 per cent, but the red rock has more than either, 8.33 per cent. Some differentiation must have occurred in this case, and probably in all similar contacts, many of which have been listed by Bowen.[1]

If it is granted that differentiation occurred, it is easily shown that local assimilation has been relatively slight. The composition of any known differentiate would become evidently hybrid with small additions of the sediments near by.

Deep-seated assimilation and differentiation—syntexis—may have occurred, but there is little evidence that it played much part in forming red rock. There are several examples of assimilation in the gabbro. The quartz gabbro described by Winchell[2] is near an inclusion of quartzite. Similar endomorphic contact effects are exposed in other parts of the gabbro. None of the assimilation phases resembles red rock.

It is therefore maintained that the granites associated with the Duluth gabbro were dependent more on differentiation than on assimilation of acid rocks. The general discussion of the processes by which granites separate from gabbro magma would be mostly theoretical and too long for this paper, but one theory has been forced into prominence by local observations on the gabbro. The several occurrences may all be explained by supposing that the original magma contained some vapors under pressure and that these tended to separate and escape from the main magma, bearing with them those acid, alkaline constituents for which they seem to have a special affinity. The accumulation of a definite upper zone of red rock would then be the result of a quiet rise of the lighter vaporous separate under an impervious roof. The aplitic areas near the top would be similar gravitative separates, disturbed by

[1] N. L. Bowen, "The Gowanda Lake District, Ontario," *Jour. Geol.*, XVIII, 658.

[2] A. N. Winchell, "The Gabbroid Rocks of Minnesota," *Am. Geol.*, XXVI, 348.

some movements at about the time of solidification. The pegmatites and aplites below would be located not so much by gravity as by simple vaporous tension; the lighter separate, being more fluid, might penetrate cracks on any side of the magma chamber in advance of the main magma. The red rock at the borders of siliceous sediments and filling the pores of sandstones as a cement may similarly have escaped from the magma under the tension of the vapors. The position of such a red-rock zone may be determined less by gravity than by porosity. The vaporous solution could escape through the pores in advance of the gabbro. In an extreme case this separation of red rock might even be determined by a porous inclusion. However, the most favorable conditions for the accumulation of red rock must be the combination of a large body of magma with plenty of water and a sandstone roof having a tight cover above.

RELATION OF ROCK TYPES TO POSITION

It is estimated that over two-thirds of the gabbro mass at Duluth consists of olivine gabbro, varying only slightly from the average. Such average rocks are scattered from top to bottom. On the other hand, specialized types have a more limited range. The peridotite occurs only near the base; the magnetite gabbro, equally heavy, is near the center; the anorthite ranges from the center toward the top and is largely in the thin earlier intrusion. Very locally at the base of the early gabbro there is an apatitic hypersthene gabbro. The occurrence of red rock, mostly near the top and in a sill at a higher horizon, is emphasized above.

DIFFERENTIATION

Introduction.—It must be granted, in regard to the Duluth lopolith, that a magma supply was available, and, as indicated by the earlier flows in the same region, it varied from time to time or place to place. The problem of its history as a lopolith begins with its intrusion into the present chamber. Various theories are current as to the processes by which a magma during such a history gives rise to a series of rock types instead of a single one. The roof of the magma for much of its area was diabase and too much like the

magma to indicate that assimilation after intrusion could yield new types. Successive intrusions certainly differed slightly, and it is likely that some parts of the earlier magma were very nearly of the composition of anorthosite. However, although this early magma is different from the later, larger intrusion, there is no sign that the variety in the main gabbro is due to successive intrusions. If this main gabbro was heterogeneous when intruded there was plenty of time for it to become mixed, unless the tendency of the parts was to become more distinct rather than to mix. It therefore seems that the main development of variety in the lopolith depended on processes of differentiation. The variety of rocks described above shows how thorough this differentiation was.

Processes of differentiation.—Recent experimental work is very conclusive in maintaining the reality of crystal settling in a magma and the improbability of extended diffusion as factors in differentiation. It is much less conclusive in dismissing convection and assimilation and the separation of immiscible fractions of magmas.[1] There are some evidences at Duluth which indicate the processes involved.

Crystal settling versus convection.—One of the first considerations in a study of crystal settling concerns the plagioclase. The mass was so large that at Duluth the crystals must have grown very slowly, for the most part too slowly to yield zoned structures. With such very slow cooling a plagioclase would begin to crystallize with a composition much more basic than would be calculated from an average of the magma; but as crystallization proceeded it might have readjusted itself to the magma, so changed in composition as finally to be the plagioclase indicated by the composition of the average magma. This adjustment is supposedly interfered with in cases of very slow cooling, hence to be expected at Duluth, by the settling or floating of the early basic crystals out of reach of the residual liquid. The crystals should then be more basic plagioclase wherever the early crystals accumulated and more acid elsewhere.[2] Let us see how the Duluth gabbro fits the case.

[1] N. L. Bowen, "Later Stages in the Evolution of Igneous Rocks," *Jour. Geol.*, XXIII (1915), supplement to the December number.

[2] F. L. Bowen, *ibid.*, p. 33.

Nearly all the feldspar of the gabbro, through a thickness of three miles, is basic labradorite or acid bytownite, with surprisingly little variation and no apparent relation between position and the slight variations found. Near the top for a few feet the feldspars are zoned, and directly above is the red rock in small amount. Can 15,000 feet of bytownite, Ab_1An_2, settle out of a magma of more acid composition without changing the composition of the residual liquor, so as to produce a notable change in the crystals forming? And, if so, can 15,000 feet of bytownite, Ab_1An_2, settle from a mother liquor that amounts to less than 300 feet of acid andesine? It is evidently absurd to think that the main gabbro settled, leaving a mother liquor of red rock in such small amount. The gabbro feldspars are too uniform. The early crystals, which were very basic according to theory, forming from a labradorite melt, must have remained in contact with the mother liquor until equilibrium was established and they became average in composition. The crystals may have settled a little, but the viscous magma more than likely moved with them in convection most of the way. The end of crystallization came when the crystals lodged in the more viscous wall or floor, and there slowly, maintaining equilibrium, the crystals adjusted their composition to that of the magma around them, some bytownite, some labradorite.[1]

In connection with crystal settling the gravitative position of differentiates is cited as strong confirmation. The Duluth gabbro is supposed to be one of the best illustrations, since it is commonly thought that magnetite separated at the base. As a fact, the segregated ores are far from the base; the best concentrations are bands centrally placed in banded gabbro. Ores near the base are contact ores or xenoliths, and the gabbro at the base shows very

[1] The mechanics of the convection has been outlined elsewhere. See Frank F. Grout, "Two-Phase Convection in Igneous Magmas," *Jour. Geol.*, XXVI (1918), 481.

Another more general criticism of crystal settling may be noted at this time. Bowen records in the *Am. Jour. Sci.*, XXXIX, 175, that crystals grow during settling in a crucible from an infinitesimal start to one-tenth of a millimeter, in settling 15 millimeters. How far-fetched it is then to think of the grains of common igneous rocks as having settled thousands of feet in a laccolith or batholith! Crystal settling is an idea to think of in terms of a few feet rather than in hundreds of feet.

little enrichment in magnetite.[1] Weinschenk is authority for the statement that this is a general rule in the segregation of magnetite.[2]

Fig. 8 shows the specific gravities of the rocks of which there are data in their "stratigraphic" sequence. A curve has been drawn to indicate in a greatly generalized way the decrease in

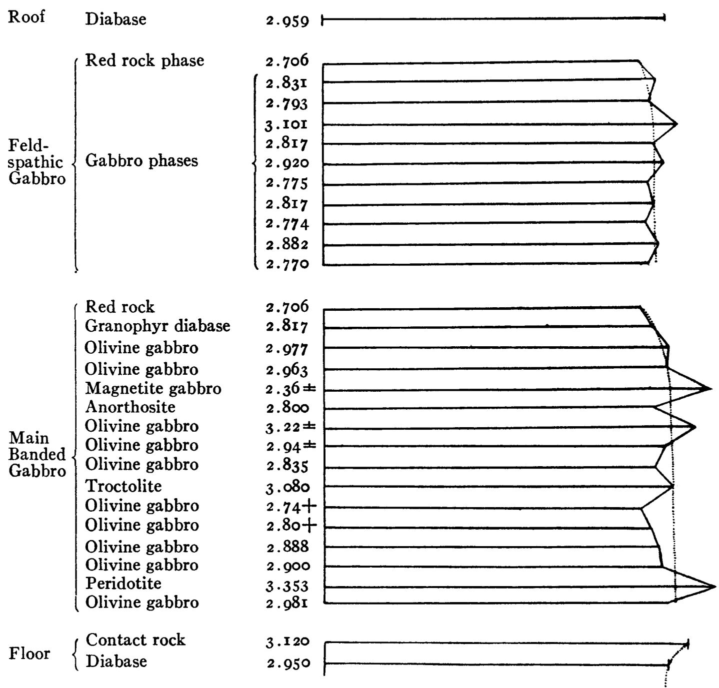

FIG. 8.—Specific gravities of Duluth rocks in "stratigraphic" order

specific gravity toward the top of the mass at Duluth, but when the data are studied in detail it is found that the curve is hardly justified. One of the heaviest rocks found was well above the center. It is thought that many of the cited examples of gravitative arrangement will show in detail the same erratic curve.

How is this irregular specific-gravity series explained? The idea of crystal settling has not been so stated as to cover it. The

[1] T. M. Broderick, "The Relation of the Titaniferous Magnetites of Northeastern Minnesota to the Duluth Gabbro," *Econ. Geol.*, XII (1917), 663.

[2] Dr. E. Weinschenk, translation by A. Johannsen, "The Fundamental Principles of Petrology." McGraw-Hill Co. (1916), p. 45.

idea of convection with a rhythm of crystallization would lead one to expect exactly what is here found.[1] The first crystals to form, if not altogether too light, would be the first to drag along the bottom. The heavy minerals would take their turn, and the magnetite being, at least partly, later in time of crystallization would remain liquid until the lower parts of the chamber were filled with layers of rock. Thus both the uniform feldspar and the curve of gravity may be taken as signs of convection.

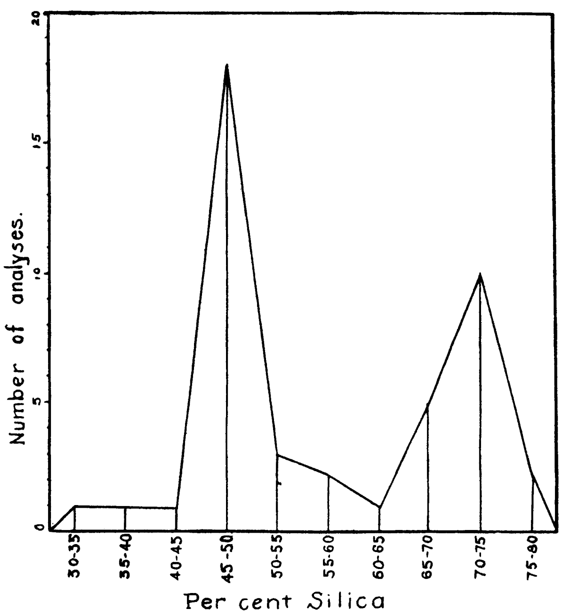

FIG. 9.—Silica content of specimens of the Duluth gabbro formation

Double differentiation.—A second feature of the rocks of the lopolith, which has a bearing on the process of differentiation, is the apparent break in the series. This is evident in plotting curves of variation in chemical or mineralogic constituents, and even more strikingly in a mathematical arrangement of the quantitative classification. Nothing in the outline of crystallization differentiation leads one to expect any sudden changes in rock types or any omissions in the series of intermediate rocks. A mass of rock with

[1] Frank F. Grout, "Two-Phase Convection in Igneous Magmas," *Jour. Geol.*, XXVI (1918), 481.

alkali feldspar is derived from gabbro only when a similar or larger amount of rock has separated with a medium to acid labradorite or andesine. No such rock is known at Duluth, though the small transition zones do exhibit zoned feldspars.

The arrangement of analyses according to the per cent of silica shows two well-defined and separated groups, one about 47 per cent silica and one about 72 per cent silica (see Fig. 9). The groups are evidently related to the two groups distinguished as gabbro and red rock. All the red rock contains more than 57 per cent silica;

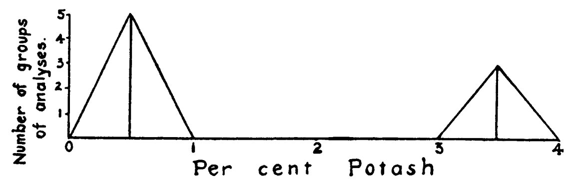

FIG. 10.—The potash content of the Duluth gabbro formation, as shown by available analyses (in groups).

no gabbro has as much as 57 per cent. The break appears even more sharply when the analyses are arranged in the order of silica per cent and a curve is drawn for the per cent of potash (see Fig. 10). All the groups of red rock analyses have more than three per cent of potash, while the gabbro groups all have less than 1 per cent. Although single analyses may show exceptional figures there is no real overlap.[1]

[1] Silica per cent	Potash per cent In detail	Potash per cent By groups	
2.02	0		
32.90	0+	0.17	
35.81	0.33		
42.24	0.27		
45.65	1.05		
45.66	0.41		
46.45	0.34	0.56	
47.05	0.05		
47.10	0.92		
47.25	0.37		
47.79	0.53		
47.90	0.56	0.66	Gabbro
48.20	0.32		
49.15	1.61		
49.18	0.82		
49.39	0.10		
49.42	1.15	0.71	
49.78	0.46		
49.88	0.68		
50.43	0.34		
50.86	0.90		
52.48	1.75	0.95	
53.43	1.12		
56.60	0.45		

Silica per cent	Potash per cent In detail	Potash per cent By groups	
57.98	3.44		
61.09	3.65		
65.56	2.88	3.20	
66.36	3.05		
66.92	3.98		
68.36	4.48		
71.15	2.40		
71.81	1.92	3.66	Red rock
72.42	4.97		
73.28	4.50		
73.70	4.56		
73.91	2.78	3.18	
74.00	4.33		
75.78	1.06		

It is not suggested for a moment that the series at Duluth does not include all types in complete gradation, but the gradation zone is small, and the separation of two types is very complete. Even though some samples were selected to show intermediate rocks, the analyses show that they belong distinctly to one side or the other of a break in the series.

When these sharply divided groups are studied in detail, each is found to vary widely without crossing the limits of the group to

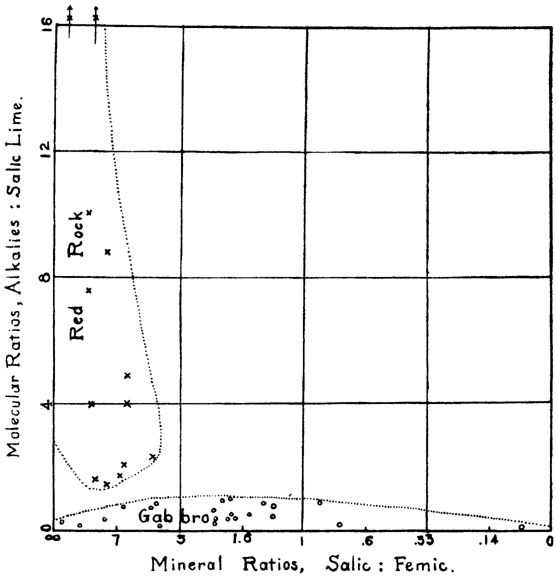

FIG. 11.—Diagram based on Duluth analyses, showing that the variation in the gabbro is in a different direction from the variation in the red rock. While the gabbro varies from salic to femic, it never becomes alkalic. While the red rock varies from alkalic to calcic, it nowhere becomes femic.

approach the other. There is no way to arrange all the gabbros in a single linear series, but this complexity in the gabbro group is entirely aside from the series grading toward red rock. It is a gradation of a really different character (see Fig. 11).

One series of rocks from peridotite to olivine gabbro and anorthosite, with some side branches to magnetitic gabbro and troctolite, varies chiefly in the quantities of minerals—labradorite, augite, olivine, and magnetite. In the main course of variation all four

gabbro minerals are present and the composition of minerals is surprisingly uniform throughout. When any mineral differs from the average the variation is not visibly related to the position or to the associated minerals.

A second type of variation is that from the general gabbro type to the granophyr. This is a change in mineral composition as well as a change in the essential minerals present (see Fig. 12). In the field this change comes with surprising abruptness, after the

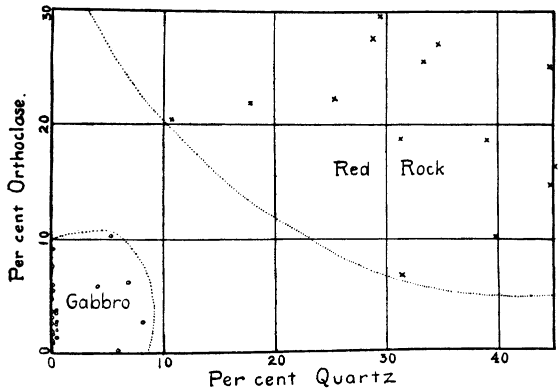

FIG. 12.—Diagram showing the break between gabbro and red rock at Duluth when plotted on the basis of quartz and orthoclase content.

monotony of slightly varying gabbro bands, with an extreme only occasionally. In a few feet after the reddish tinge of granophyr is seen in the interstices of the gabbro none of the gabbro minerals are visible in the rock.

This double process is distinctly contrary to the idea of Bowen's paper, and there are few suggestions of the sort in the literature. There are, indeed, suggestions of different types of differentiation. Bowen outlines two series from gabbro to alkaline types.[1] Harker has contrasted regional and local action.[2] Lane speaks of wet and dry differentiation.[3] However, there is evidence at Duluth of two

[1] N. L. Bowen, "Later Stages in the Evolution of Igneous Rocks," *Jour. Geol.*, XXIII (1915), December Supplement, p. 77.

[2] A. Harker, "Tertiary Igneous Rocks of Skye," *Mem. Geol. Survey of the United Kingdom* (1904), p. 419.

[3] A. C. Lane, "Wet and Dry Differentiation," *Tufts College Studies*, III, 39.

contrasting series in a single mass cooling in a single chamber, and a study of the literature of other districts makes it seem likely that this double sequence is a common thing.

The association of both granophyr and anorthosite as differentiates of normal gabbro is too common to have escaped observation. Each rock requires large bodies of magma for its production and each is of low specific gravity. Several geologists discuss these rocks as normal differentiates of gabbro, but no one has developed a satisfactory explanation of the manner in which the two rocks form. To be sure, a line of descent can be stated so that both are mentioned, but the suggested origin would lead one to expect them in very different field relations from those at Duluth. Thus, when peridotite, troctolite, and olivine gabbro had separated from the magma, the feldspar should begin to grow more acid and the olivine less abundant; but no such relation appears. Later, considerable magma of dioritic composition might yield crystals of gabbroic nature while itself as a liquid approaching the composition of a granite. However, before it reaches the composition of such a granophyr as the red rock of Duluth a large amount of feldspar must have crystallized from a magma too acid to yield basic labradorite; that is, at some stage, a quantity of diorite and granodiorite must have separated. No such rocks appear. Instead, there is a very narrow zone of granophyr diabase, in which the feldspars, to be sure, are zoned according to theory; but the zone is too small to yield the masses of red granophyr actually found.

Thus the characteristic rock series at Duluth is neither of Bowen's recognized series:[1] "gabbro, diorite, quartz diorite, granodiorite, granite"; nor "gabbro, diorite, syenite, granite." The series is rather (1) gabbro, (2) granophyr diabase, (3) granite, with the second member very small in bulk. This is believed to be a common sequence. Harker recently called attention to the general lack of intermediate rocks in such rock masses.[2]

[1] *Loc. cit.*

[2] A. Harker, "Differentiation in Intercrustal Magma Basins," *Jour. Geol.*, XXIV, 554.

TABLE I

CHEMICAL ANALYSES—GABBRO FROM DULUTH

	1	2	3	4	5	6	7	8	9*	10	11
Silica SiO_2	48.20	32.90	49.39	47.10	42.24	35.81	52.48	45.65	49.15	49.42	50.43
Alumina Al_2O_3	19.53	1.59	29.08	12.92	18.50	14.32	15.47	15.20	21.90	24.47	23.83
Ferric oxide Fe_2O_3	Trace	13.25	0.34	12.95	4.68	7.38	5.14	6.71	6.60	3.13	17.63
Ferrous oxide FeO	10.60	21.06	2.89	9.46	14.50	15.25	9.25	13.81	4.54	6.13	
Magnesia MgO	9.28	20.14	2.26	3.08	2.76	10.49	2.55	2.95	3.03	1.00	2.46
Lime CaO	8.51	0.50	13.06	10.29	10.36	7.23	7.27	6.33	8.22	8.45	4.79
Soda Na_2O	2.52	Trace	2.89	2.61	2.19	2.06	3.26	3.09	3.83	4.98	2.06
Potash K_2O	0.32	Trace	0.10	0.92	0.33	0.37	1.75	1.05	1.61	1.15	0.34
Combined water H_2O+	0.65	4.56	0.34	0.71	1.80	5.25	1.24	2.29	1.92	0.55	...
Moisture H_2O-	0.08	0.55	0.09	0.12	0.25	...	...	...	...	0.06	...
Carbon dioxide CO_2	0.02	0.10	Trace	...	1.67	Traces	...	...	...	...	...
Titania TiO_2	0.65	5.36	Trace	1.38	1.16	2.30	1.26	1.66	0.18	1.87	Trace
Phosphorus oxide P_2O_5	0.19	Trace	0.09	0.01	0.19	...	0.29	0.25	0.33	0.04	...
Sulphur S	0.03	0.05	None	...	...	...	...	...	...	0.11	...
Chromium oxide Cr_2O_3	Trace	0.04	Trace	...	...	...	...	...	...	...	...
Copper oxide Cu_2O	...	0.15	...	...	...	...	...	...	...	...	...
Manganous oxide MnO	0.14	0.40	0.04	0.80	0.13	0.18	0.51	0.71	...	0.11	...
Rarer elements	Trace	0.06	None	...	...	...	Traces	Traces	...	...	...
	100.72	100.71	100.57	101.63	100.76	100.62	100.47	99.70	100.80*	101.48	101.54
Specific gravity	2.963	3.353	2.770	...	...	3.07–3.10	2.81–2.84	2.84–2.86	...	...	2.79–2.802

* Original summation did not include P_2O_5 and TiO_2.

TABLE I—*Continued*

Norms and Classification

	1	2*	3	4*	5	6	7	8	9	10	11†
Quartz	....	....	....	....	....	....	5.6	....	....	....	....
Orthoclase	1.67	....	0.56	5.56	1.67	2.22	10.6	6.1	9.45	7.23	....
Albite	21.48	....	24.63	22.01	18.34	7.86	27.2	26.2	31.96	32.49	....
Anorthite	40.59	2.50	63.94	20.57	39.75	28.63	22.5	24.5	38.09	40.59	....
Nephelite	....	....	....	....	....	5.11	....	....	....	5.40	....
Corundum	....	....	0.71	....	....	....		....	....	....	....
Diopside	0.68	10.88	....	26.16	9.28	5.91	11.4	5.2	0.68	1.18	....
Hypersthene	12.54	4.85	6.34	9.26	4.27	....	11.6	19.5	4.16	....	....
Olivine	21.20	62.60	3.14	5.34	14.24	30.41	....	1.7	4.12	11.79	....
Magnetite	....	0.93	0.46	12.02	6.73	10.67	7.4	9.7	9.51	4.41	....
Ilmenite	1.22	8.43	....	2.74	2.28	4.41	2.4	3.2	0.30	3.50	....
Apatite	0.34	....	0.34	....	.34	....	.5	.5	.67	....	....

* Estimate based on the known secondary oxidation of part of the iron.

† "Not good for classification." H.S.W., PP 14, p. 431.

	1	2*	3	4*	5	6	7	8	9	10	11†
	Dosalic Perfelic Docalcic Persodic	Perfemic (Perfelic) (Docalcic)	Persalic Perfelic Docalcic Persodic	Salfemic Perfelic Alkalicalcic Dosodic	Salfemic Perfelic Docalcic Persodic	Salfemic Perfelic Docalcic Persodic	Dosalic Perfelic Alkalicalcic Dosodic	Salfemic Perfelic Alkalicalcic Dosodic	Dosalic Perfelic Docalcic Dosodic	Dosalic Perfelic Alkalicalcic Dosodic	(Persalic) (Dofelic) (Docalcic) (Persodic)
	Hessose II.5.4.5	.... V.5.4.–	Labradorose I.5.4.5	Camptonose III.5.3.4	Auvergnose III.5.4.5	Auvergnose III.5.4.5	Andose II.5.3.4	Camptonose III.5.3.4	Hessose II.5.4.4	Andose II.5.3.4	....

1. Olivine Gabbro. Sec. 23, T. 49 N., R. 15 W., West Duluth. F. F. Grout.
2. Peridotite. Sec. 34, T. 49 N., R. 15 W., Short Line Park. F. F. Grout.
3. Anorthosite Sec. 19, T. 50 N., R. 14 W., North of Proctor. F. F. Grout
4. Olivine Gabbro. Sec. 33, T. 49 N., R. 15 W., Short Line Park. G. S. Nishihara.
5. Gabbro Pegmatite. Sec. 33, T. 49 N., R. 15 W., Short Line Park. G. S. Nishihara
6. Troctolite. Sec. 22, T. 50 N., R. 15 W., North of Proctor. A. N. Winchell. *Am. Geol.*, XXVI, 284.
7. Orthoclase Gabbro. Down town at Duluth. A. N. Winchell. *Am. Geol.*, XXVI, 293.
8. Hornblende Orthoclase Gabbro. Down town at Duluth. A. N. Winchell. *Am. Geol.*, XXVI, 293.
9. Hornblende Gabbro. At Duluth. A. Streng. *Neues Jahrbuch für Mineralogie, Geologie und Paleontologie*, 1877, p. 113.
10. Gabbro, probably of the feldspathic type. Near the center of Sec. 33, T. 50 N., R. 14 W., Duluth. G. H. Stone. *Jour. Geol.*, XVIII, 656.
11. Gabbro, feldspathic type. Sec. 34, T. 50 N., R. 14 W., Duluth. J. A. Dodge. *Minn. Geol. and Nat. Hist. Survey, Final Rep.*, V, 85.

TABLE I—*Continued*

ANALYSES OF DULUTH GABBRO, NORTHEAST OF THE TYPE LOCALITY

	12	13	14	15	16	17	18
Silica SiO_2	2.02	45.66	46.45	47.70	47.90	53.43	56.60
Alumina Al_2O_3	2.68	16.44	21.30	19.04	19.92	13.81	17.84
Ferric oxide Fe_2O_3	80.78	0.66	0.81	0.87	4.92	5.08	2.55
Ferrous oxide FeO		13.90	9.57	8.84	9.78	9.86	4.09
Magnesia MgO	....	11.57	7.90	8.65	4.55	4.64	3.16
Lime CaO	Trace	7.23	9.83	8.96	8.56	8.25	6.28
Soda Na_2	....	2.13	2.14	2.53	2.75	2.51	4.45
Potash K_2O	....	0.41	0.34	0.53	0.56	1.12	0.45
Combined water H_2O+	....	0.83	1.02	1.38	0.76	0.27	3.20
Moisture H_2O-	....	0.07	0.14	....	....	....	....
Carbon dioxide CO_2	....	....	....	Trace	n.d.	....	n.d.
Titania TiO_2	12.09	0.92	1.19	1.80	0.57	....	1.59
Phosphorus oxide P_2O_5	0.03	0.05	0.02	n.d.	n.d.	....	0.14
Chromium oxide Cr_2O_3	2.40	Trace	....	....	....	....	....
Manganous oxide MnO	....	Trace	Trace	Trace	....	Trace	....
Nickel oxide NiO	....	0.16	0.04	....	....	....	....
Other elements	....	....	....	Traces	Traces	....	Traces
	99.90	100.03	100.75	100.30	100.27	98.97	100.35
Specific gravity	....	....	....	2.89	2.93	....	2.38*

* Evidently an error but correctly quoted.

TABLE I—*Continued*

NORMS AND CLASSIFICATION

	12	13	14	15	16	17	18
Quartz	....	....	....	....	....	7.68	8.9
Orthoclase	....	2.2	1.7	2.8	3.3	6.67	2.8
Albite	....	17.8	17.8	21.0	23.1	20.96	37.7
Anorthite	....	34.2	47.8	39.2	40.0	23.07	27.2
Diopside	....	1.4	0.8	4.5	2.0	14.78	3.4
Hypersthene	....	10.1	11.1	12.7	19.8	18.10	11.5
Olivine	....	30.3	16.8	13.9	1.8	....	....
Magnetite } Ilmenite }	95.27	0.9	1.2	1.4	7.2	7.42	3.7
Ilmenite		2.6	2.3	3.4	1.1	....	3.1
Apatite	....	....	....	....	....	....	....
	Perfemic	Salfemic	Dosalic	Dosalic	Dosalic	Salfemic	Dosalic
	(Perfelic)	Perfelic	Perfelic	Perfelic	Perfelic	Dofelic	Perfelic
	....	Docalcic	Docalcic	Docalcic	Docalcic	Docalcic	Alkalicalcic
	....	Persodic	Persodic	Persodic	Persodic	Dosodic	Persodic
	X	Auvergnose	Hessose	Hessose	Hessose	X	Beerbachose
	V.5—	III.5.4.5	II.5.4.5	II.5.4.5	II.5.4.5	III.4.4.4	II.5.3.5

12. Gabbro magnetite. On the south side of Iron Lake, Sec. 36, T. 65 N., R. 3 W. R. S. Robertson. *Minn. Geol. and Nat. Hist. Survey Bull. 6*, p. 141.
13. Gabbro. Sec. 19, T. 63 N., R. 9 W. H. N. Stokes. *Jour. Geol.*, I, 712.
14. Gabbro, representative. Sec. 35, T. 61 N., R. 12 W. H. N. Stokes. *Jour. Geol.*, I, 712.
15. Olivine Gabbro. Birch Lake. H. N. Stokes. *Am. Geol.*, XXVI, p. 181.
16. Diabase Gabbro. East side of Birch Lake. A. N. Winchell. *Am. Geol.*, XXVI, 374.
17. Gabbro with quartz. Endomorphic contact rock. Sec. 11, T. 63 N., R. 5 W. Dodge and Sidener. *Minn. Geol. and Nat. Hist. Survey, Final Rep.* V, 543.
18. Quartz Gabbro. Sec. 12, T. 64 N., R. 6 W. Little Saganaga Lake. A. N. Winchell. *Am. Geol.*, XXVI, p. 352.

TABLE I—*Continued*

ANALYSES OF SILLS AND MASSES SUPPOSED TO BE RELATED TO THE DULUTH GABBRO

	19	20	21	22	23	24
Silica SiO_2	49.18	49.88	50.86	47.25	49.78	47.05
Alumina Al_2O_3	19.01	18.55	15.72	31.56	29.37	32.03
Ferric oxide Fe_2O_3	0.89	2.06	9.77	...	0.34 }	2.01
Ferrous oxide FeO	7.79	8.37	2.48	2.29	0.60 }	
Magnesia MgO	6.42	5.77	3.55	0.27	1.07	0.15
Lime CaO	9.12	9.70	10.52	15.39	11.86	15.85
Soda Na_2O	3.32	2.59	3.89	2.52	4.39	1.00
Potash K_2O	0.82	0.68	0.90	0.37	0.46	0.05
Combined water H_2O+	2.06	1.04	2.53	0.40	1.76	1.36
Moisture H_2O-	...	...	...	...	...	...
Carbon dioxide CO_2	Trace	...	...	...	...	...
Titania TiO_2	1.09	1.19	...	...	None	...
Phosphorus oxide P_2O_5	...	0.16	...	...	Traces	...
Manganous oxide MnO	0.51	0.09	...	...	0.08	...
Barium oxide BaO	None	0.02	...	...	None	...
Other elements	Traces	...	...	...	Traces	...
	100.21	100.21	100.22	100.05	99.80	99,50
Specific gravity	2.84	2.923–2.970	...	About 2.7	2.676	...

TABLE I—*Continued*

ANALYSES OF RED-ROCK INTRUSIVES AT DULUTH

	25	26	27	28
Silica SiO_2	66.92	66.36	75.78	65.56
Alumina Al_2O_3	12.51	13.33	11.09	10.06
Ferric oxide Fe_2O_3	4.36	7.89	2.09	14.40
Ferrous oxide FeO	3.93	2.96	...	0.23
Magnesia MgO	1.66	1.20	0.65	0.73
Lime CaO	1.20	2.14	0.86	0.96
Soda Na_2O	3.45	2.63	6.43	2.25
Potash K_2O	3.98	3.05	1.06	2.88
Combined water H_2O+	1.25	1.21	1.82	0.86
Moisture H_2O-	0.20	...	...	...
Carbon dioxide CO_2	0.02	...	...	...
Titania TiO_2	0.69	...	...	...
Zirconia ZrO_2	0.22	...	...	...
Phosphorus oxide P_2O_5	0.11	...	...	...
Sulphur S	0.04	...	...	...
Manganous oxide MnO	0.16	...	...	...
Barium oxide BaO	0.06	...	...	...
	100.76	100.77	99.78	97.93
Specific gravity	2.721	...	...	...

TABLE I—*Continued*

NORMS AND CLASSIFICATION

	19	20	21	22	23	24
Quartz	...	...	3.2	...	...	6.60
Orthoclase	5.00	3.9	5.6	2.22	2.8	...
Albite	27.77	22.0	33.0	15.20	28.8	8.38
Anorthite	34.47	37.0	22.5	73.40	58.7	78.68
Nephelite	...	...	...	3.41	4.5	...
Corundum	...	...	...	...	...	1.53
Diopside	8.90	8.9	19.3	2.67	...	...
Hypersthene	2.76	21.8	...	...	...	1.46
Olivine	15.74	...	...	2.70	2.5	...
Magnetite	1.39	3.0	8.1	...	0.5	1.39
Ilmenite	2.13	2.3	...	...	...	...
Hematite	...	...	4.2	...	...	...
Wollastonite	...	...	2.0	...	...	...
	Dosalic Perfelic Docalcic Dosodic	Dosalic Perfelic Docalcic Dosodic	Dosalic Perfelic Alkalicalcic Dosodic	Persalic Perfelic Docalcic Persodic	Persalic Perfelic Docalcic Persodic	Persalic Perfelic Percalcic Persodic
	Hessose	Hessose	Andose	Labrado-rose	Labrado-rose	Persodic Canadase
	II.5.4.4	II.5.4.4	II.5.3.4	I.5.4.5	I.5.4.5	I.5.5.5

19. Olivine diabase. Pigeon Point. A. N. Winchell. *Am. Geol.*, XXVI, 213.
20. Olivine gabbro. Pigeon Point. W. F. Hillebrand. *U.S. Geol. Survey Bul. 109*, p. 63.
21. "Altered Gabbro. East of Baptism River." Dodge and Sidener. This probably is "Beaver Bay diabase." *Minn. Geol. and Nat. Hist. Survey Bul. 2*, p. 79.
22. Anorthosite. At mouth of Split Rock River, quoted from R. D. Irving. *U.S. Geol. Survey Mon.*, V, p. 438.
23. Anorthosite. Carlton Peak. A. N. Winchell. *Am. Geol.*, XXVI, 281.
24. Anorthosite. At the foot of Caribou Peak. C. F. Sidener.

TABLE I—*Continued*

NORMS AND CLASSIFICATION

	25	26	27	28
Quartz	25.50	33.00	33.00	38.28
Orthoclase	23.91	17.79	6.67	17.24
Albite	28.82	22.53	50.83	18.86
Anorthite	5.28	10.56	...	4.73
Corundum	0.61	1.73	...	1.53
Zircon	0.37	...	...	...
Diopside	...	...	3.24	...
Hypersthene	6.87	3.00	0.10	1.80
Acmite	...	...	3.23	...
Magnetite	6.26	9.51	...	0.93
Ilmenite	1.37	...	...	...
Hematite	...	1.28	0.96	13.76
Apatite	0.34	...	...	...
	Dosalic Dofelic Domalkalic Sodipotassic	Dosalic Quarfelic Domalkalic Sodipotassic	Persalic Dofelic Peralkalic Persodic	Dosalic Quarfelic Domalkalic Sodipotassic
	Adamellose	X	Noyangose	X
	II.4.2.3	II.3.2.3	I.4.1.5	II.3.2.3

25. Red Rock. N.W. corner Sec. 27, T. 50 N., R. 14 W. F. F. Grout.
26. Red Granite. Rice's Point, Duluth. J. A. Dodge. *Minn. Geol. and Nat. Hist. Survey, 13th Ann. Rep.*, p. 100.
27. Red Granite. Rice's Point, Duluth. J. A. Dodge. *Minn. Geol. and Nat. Hist. Survey, 10th Ann. Rep.*, p. 204.
28. Red Granite. East of Lester River, East Duluth. J. A. Dodge. *Minn. Geol. and Nat. Hist. Survey, 13th Ann. Rep.*, p. 100.

TABLE I—*Continued*

ANALYSES OF RED-ROCK INTRUSIVES NORTHEAST OF DULUTH SUPPOSED TO BE RELATED TO THE DULUTH GABBRO

	29	30	31	32	33	34	35	36	37	38
Silica SiO_2	57.98	61.09	68.36	72.42	74.00	73.91	73.70	71.15	71.81	73.28
Alumina Al_2O_3	13.58	15.34	13.76	13.04	12.04	14.89	12.87	12.40	12.82	11.83
Ferric oxide Fe_2O_3	3.11	5.74	2.65	0.68	0.78	2.27	3.76	5.21	6.02	4.61
Ferrous oxide FeO	8.68	3.69	2.75	2.49	2.61	1.70	0.31	0.75		0.56
Magnesia MgO	2.87	1.33	0.68	0.58	0.42	Trace	0.11	1.13	0.56	0.36
Lime CaO	2.01	3.10	0.70	0.66	0.85	0.27	0.14	1.90	2.26	1.04
Soda Na_2O	3.56	3.41	3.56	3.44	3.47	2.64	3.63	1.70	2.51	1.66
Potash K_2O	3.44	3.65	4.48	4.97	4.33	2.78	4.56	2.40	1.92	4.50
Combined water H_2O+	2.47	1.80	0.98	1.21	0.86	1.01	0.57	2.12	....	1.82
Moisture H_2O-	....	....	....	....	....	....	....	....	....	....
Titania TiO_2	1.75	....	1.57	0.40	0.34	....	0.12	....	....	....
Phosphorus oxide P_2O_5	0.29	....	0.33	0.20	0.06	....	Trace	....	....	....
Sulphuric oxide SO_3	....	....	0.66	....	....	....	....	....	....	....
Manganous oxide MnO	0.13	....	....	0.09	0.05	....	0.07	....	....	....
Barium oxide BaO	0.04	....	....	0.15	0.12	....	....	....	....	....
Other elements	Traces	....	....	Traces	Traces	....	....	....	....	....
	99.91	99.15	100.48	100.37	99.93	99.47	99.84	98.76	97.90	99.66
Specific gravity	....	....	....	2.620	2.565	....	....	....	....	....

TABLE I—*Continued*

NORMS AND CLASSIFICATION

	29	30	31	32	33	34	35	36	37	38
Quartz	11.1	17.7	28.0	29.4	33.2	46.44	34.7	45.12	40.08*	43.44
Orthoclase	20.0	21.2	26.7	30.0	25.6	16.68	27.2	14.46	11.12	26.69
Albite	29.9	28.8	29.9	28.8	29.3	22.53	30.4	14.15	20.96	14.15
Anorthite	10.0	15.3	3.3	3.2	4.2	1.39	0.6	9.45	11.12	5.28
Corundum	0.5	....	1.8	0.8	....	6.94	1.7	3.57	2.55	2.24
Hypersthene	17.7	5.4	1.9	5.0	4.6	1.32	0.3	2.80	11.30	0.90
Magnetite	8.0	8.1	3.9	0.9	1.2	3.25	0.9	2.55	....	1.87
Ilmenite	3.4	....	3.1	0.8	0.6	....	....	....	....	....
Hematite	....	....	....	....	....	....	3.2	3.52	....	3.36

* Assuming that some ferric iron is secondarily oxidized, as is evident.

	29	30	31	32	33	34	35	36	37	38
	Dosalic Dofelic Domalkalic Sodipotassic	Dosalic Dofelic Domalkalic Sodipotassic	Persalic Dofelic Peralkalic Sodipotassic	Persalic Dofelic Peralkalic Sodipotassic	Persalic Dofelic Domalkalic Sodipotassic	Persalic Quarfelic Peralkalic Sodipotassic	Persalic Dofelic Peralkalic Sodipotassic	Persalic Quarfelic Alkalicalcic Sodipotassic	Persalic Quarfelic Alkalicalcic Dosodic	Persalic Quarfelic Domalkalic Dopotassic
	Adamellose	Adamellose	Liparose	Liparose	Toscanose	Alaskose	Liparose	Riesenose	Dosodic Riesenase	Mihalose
	II.4.2.3	II.4.2.3	I.4.1.3	I.4.1.3	I.4.2.3	I.3.1.3	I.4.1.3	I.3.3.3	I.3.3.4	I.3.2.2

29. "Intermediate rock," selected to show the type of rock between gabbro and red rock. Pigeon Point. W. F. Hillebrand. *U.S. Geol. Survey Bull. 109*, p. 63.
30. Red Granite. Pigeon Point. M. E. Wadsworth. *Minn. Geol. and Nat. Hist. Survey, Final Rep.*, V, p. 303.
31. Red Rock. Pigeon Point. J. E. Whitfield. *U.S. Geol. Survey Bull. 109*, p. 90.
32. Red Rock. Pigeon Point. W. F. Hillebrand. *U.S. Geol. Survey Bull. 109*, p. 56.
33. Red Rock, porphyritic. Pigeon Point. W. F. Hillebrand. *U.S. Geol. Survey Bull. 109*, p. 56.
34. Red Rock. Island south of Pigeon Point. J. A. Dodge. *Minn. Geol. and Nat. Hist. Survey, 13th Ann. Rep.*, p. 100.
35. Red Rock, porphyritic. Little Brick Island off Pigeon Point. L. G. Eakins. *U.S. Geol. Survey Bull. 109*, p. 58.
36. Granite, pink. West side of Beaver Bay. J. A. Dodge. *Minn. Geol. and Nat. Hist. Survey, 13th Ann. Rep.*, p. 100.
37. Granite, purplish gray. West side of Beaver Bay. J. A. Dodge. *Minn. Geol. and Nat. Hist. Survey, Final Rep.*, V, 400.
38. Red Granite. Third island east of Beaver Bay. J. A. Dodge. *Minn. Geol. and Nat. Hist. Survey, 13th Ann. Rep.*, p. 100.

TABLE II

Classification of Igneous Rock Series from Several Districts

Duluth	Skye	Sudbury	Purcell	Carrock Fell	Preston	Juliana-haab	Sweden	Palisades	Gowganda	St. Davids Head	Adiron-dacks	Cortlandt
Gabbro Series	Diabase and Dolerite	Diabase and Norite	Diabase Sills	Gabbro	Gabbros		Olivine-Diabase, Peridotite, Anorthosite and Iron Ores	Diabase	Sills of Gabbro and Granophyr-Diabase	Various Gabbros	Gabbros, Anorthosite and Iron Ore	Diorite, Gabbro, Norite, Pyroxenite
I.5.4.5											I.5.4.5	
I.5.4.5												
I.5.4.5												
I.5.5.5												
									II.5.2.5			
							II.5.3.3					II.5.3.3
II.5.3.4							II.5.3.4					II.5.3.4
II.5.3.4												II.5.3.4
II.5.3.4												II.5.3.4
II.5.3.5									II.5.3.5	II.5.3.5		
		II.5.4.3									II.5.4.3	II.5.4.3
											II.5.4.3	II.5.4.3
II.5.4.4	II.5.4.–	II.5.4.4					II.5.4.4					
II.5.4.4		II.5.4.4										
II.5.4.4												
II.5.4.5	II.5.4.5			II.5.4.5								
II.5.4.5	II.5.4.5											
II.5.4.5	II.5.4.5											
II.5.4.5												
	II.5.5.5					II.6.1.4						
III.5.3.4			$\text{III.}\left\{\begin{matrix}4\\5\end{matrix}\right\}\text{.5.4}$			II.7.1.4			III.5.2.4			
III.5.3.4								III.5.3.4		III.5.3.4	III.5.3.4	
								III.5.3.4			III.5.3.4	
								III.5.3.4				
					III.5.3.5			III.5.4.4		III.5.4.4		
			III.5.4.4				III.5.4.4	III.5.4.4				
III.5.4.5			III.5.4.5		III.5.4.5			III.5.4.4				
III.5.4.5					III.5.4.5			III.5.4.4				
III.5.4.5								III.5.4.5				
		III.5.5.5						III.5.4.5				
						III.6.1.3						III.6.3.4
	IV.5.4.4						IV.5.4.4	IV.5.4.4			IV.5.4.3	IV.5.3.3
							IV.5.4.4	IV.5.4.4				IV.5.3.4
											IV.5.–.–	IV.5.3.4
											IV.6.4.4	
V.5.4.–	V.5.4.4											
V.5.–.–												

			Intermediate Rock				Monzonite					
....	....	....	II.4.4.3	....	....	....	II.4.3.4	....	....	....	....	....
Red Rock	Granophyr	Syenite and Granite	Granite		Oligoclase Granite		Granite	Granophyr-Diabase	Aplite	Aplite	Granite and Syenite	Granite
I.3.1.3											I.3.1.3	
									I.3.1.5			
I.3.2.2												
			I.3.2.3									
					I.3.2.4							
I.3.3.3												
I.3.3.4												
		I.4.1.2										
I.4.1.3							I.4.1.3					
I.4.1.3												
I.4.1.3												
				I.4.1.4						I.4.1.4		
I.4.1.5												
I.4.2.3	I.4.2.3	{I, II}4.2.3									I.4.2.3	
	I.4.2.3										I.4.2.3	
											I.4.2.3	
											I.4.2.3	I.4.2.4
											I.5.2.3	
											I.5.2.4	
II.3.2.3		II.3.2.3	II.3.2.3									
II.3.2.3												
		II.3.4.3										
		II.4.1.4				II.4.1.4						
II.4.2.3												
II.4.2.3												
II.4.2.3												
		II.4.2.4						II.4.2.4				
		II.4.2.4						II.4.3.4			II.4.3.3	
		II.4.2.4									II.5.2.3	
		II.4.2.4									II.5.3.4	

COMPARISON WITH OTHER DISTRICTS

Data from several other districts are given in Table II. The method of comparison is modeled after the mathematical statement of the quantitative classification.[1] However, instead of using different bases for distinguishing rocks of the different classes, the plan in Table II is to use the same criteria for all rocks, making the figures strictly comparable through the whole table. The first term is the class (I to V) in the quantitative system. The second expresses, by groups (1 to 9), the ratios of quartz to feldspar, or lenads to feldspar. The third and fourth terms similarly express the ratio of alkalies to the lime of salic minerals, and the ratio of potash to soda, in molecular terms. These are the figures given below the norms in Table I of analyses of the Duluth lopolith.

Scarcity of intermediate rocks.—The impression obtained from the Duluth series is carried out in the others. There are few intermediate rocks in any of the districts. The samples contrast almost as sharply as at Duluth, though none seem to have as complete a series of analyses. The main rocks of the associated sequences are members of the gabbro family and granites. One rock collected by Daly in the Purcell sills is really intermediate, and this is a rock which was carefully selected with the idea of showing its transitional nature. Probably the Swedish monzonite and some syenites of the Adirondacks are also intermediate, but the papers describing them are not very definite as to their occurrence and relation. Even if the proof of gradational types is clear, as it is at Duluth, the data may well be taken as evidence that intermediate rock is less abundant than the several types on either side of the break. The sharpness of separation of types in the field has often been noted in regions of differentiated rocks.[2] To be sure it may be argued that a collector would choose clear types rather than a mixed indefinite specimen, but the facts at Duluth argue against any such condition. Here a good series showing variations of gabbro is available; but no series connects the several gabbros with the red rock; and, as

[1] Whitman Cross, J. P. Iddings, L. V. Pirsson, and H. S. Washington, *Quantitative Classification of Igneous Rocks*. University of Chicago Press, 1903.

[2] L. V. Pirsson and W. N. Rice, "The Geology of the Tripyramid Mountain," *Am. Jour. Sci.*, XXXI, 291.

said before, some were selected with the expressed intention of showing what the intermediate rocks are like.

In several large igneous bodies one of the differentiates has assumed intrusive relations to the others. In such cases it might be assumed that the disturbance is responsible for the abrupt change from one extreme to another; possibly the large amount of intermediate rock required by theory has been eroded, or is concealed in depth. Such arguments may apply to batholiths, but not to an intrusion with a floor, especially if it is as well exposed as at Duluth. Granted that there is a lack of intermediate rock at Duluth, the corresponding lack elsewhere indicates that intermediate rocks were never formed in any large quantity.

An argument for immiscible separation.—If this apparent break in the series is as normal and characteristic as it appears from the table, it gives a rather different impression from the simple sequence that has been suggested for the results of differentiation. Some modification or restatement of the outline of crystallization differentiation may bring it into closer accord with known series, but the clear impression from the series here tabulated is that two processes have been at work either successively or simultaneously.

If crystallization differentiation produced the banded gabbro, with differentiates ranging from peridotite and iron ore to anorthosite, what other processes can be conceived which might yield the red-rock differentiate? It cannot be that one is a regional and the other a local variation, for it is all in the same chamber. It is very likely to be a contrast between wet and dry. The first type of differentiation occurs in the presence of a very small amount of water (though biotite occurs even in the gabbro); and if the crystallization results in a concentration of water in the mother liquor, a point may be reached where the water has an effect not known in the earlier stages. Even in this case it is not clear why the water concentrating gradually would not yield a series of intermediate rocks in considerable volume.

The abruptness of the gradation leads almost conclusively to the idea of a separation of an immiscible liquid. This would be favored by the increased amount of water. Water was certainly abundant, as is indicated by numerous miarolitic cavities in the

red rock. It seems doubtful if any other process than the separation of immiscible fractions could operate with the separation of crystals to give such a distinct differentiate.

SUMMARY

The rocks of the Duluth gabbro lopolith are found to fall naturally into two series, one related to the gabbro family, the other more closely to the granites. Intermediate types are rare, though in the field the gradation between types is visibly complete. The abruptness of the separation in the field as well as in the arrangements on the basis of laboratory data indicates that the process involved in the separation of granite and gabbro was of a different nature from the more easily understood process by which a variety of phases developed in the gabbro. The several modifications of the gabbro probably resulted from a differentiation by crystallization during convection, aided by a slight amount of settling of crystals. Before the solidification was complete the granitic magma must have separated from the gabbro, probably by some other process, for the process giving variety to the gabbro seemed to produce no modification in it approaching the granite. The evidence is strong that differentiation of two sorts may occur in a single magma chamber. If crystallization and settling and convection are involved in the main process, it is interesting to suggest other possibilities for the other process. The difference may be due largely to a difference in the concentration of water, but the field and laboratory studies both strongly suggest an immiscible separation of the red rock from the gabbro.

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